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Abstract. We report new results using the LLNL COMET laser to evaluate the effectiveness of different target architectures to improve the output and characteristics of the transient x-ray laser scheme. Surprising observations were found when the laser line focus irradiating a single slab Cr or Fe target was divided into two or three distinct plasma column sections with millimeter scale gaps between each plasma. The Ne-like 3p $^1S_0 \rightarrow$ 3s $^1P_1$ 28.5 nm and 25.5 nm x-ray laser lines, for Cr and Fe, respectively, were improved in beam divergence, by 2 – 3 times, and peak intensity, by up to one order of magnitude, when compared with a single plasma column of the same length or longer. This was contrary to expectations since these large-scale inhomogeneities introduced along the plasma, as well as attenuation from the cold plasma at the end of each section, would be detrimental to the x-ray propagation and amplification. Instead an injector-amplifier (IA) type process appears to be at work where the plasma gaps may be beneficially modifying the ray propagation and coupling through the high Ne-like ion gain regions. We present results showing the output of the amplifier stage with increasing length for the IA targets together with beam deflection and divergence measurements.

INTRODUCTION

The use of oscillator-amplifier or injector-amplifier designs, i.e. multiple- instead of single-stage designs, have been suggested as one way to improve the output characteristics for large, high power, laser-generated x-ray lasers. An injector-amplifier (IA) architecture was proposed in order to improve the output coherence by seeding an amplifier with a single-mode from an oscillator or injector [1]. Preliminary experiments investigating this effect on the NOVA laser were reported approximately 10 years ago [2]. Another important reason for using IA design was to mitigate against refraction effects bending the x-ray laser beam out of the gain region when target lengths exceeded 2 cm [3, 4]. This work demonstrated that with optimization of the target offset, the coupling efficiency between the two stages was maximized and the effect of refraction was reduced. More recently hybrid oscillator-amplifier schemes have been proposed by using higher order harmonics as a seed to be amplified in a fast capillary discharge gain medium [5] or a picosecond-heated solid target [6].

In many respects, the high efficiency, transient gain, tabletop x-ray lasers can also benefit from injector-amplifier designs. While the required target lengths for saturated output are considerably shorter, typically less than 1 cm, refraction can still be a limiting effect because of the extremely high gains, $g > 100\ cm^{-1}$, available in higher density regions [7]. Small deflection angles of the x-ray laser beam out of these regions may reduce the gain by 10 – 20 % or more which is sufficient to substantially decrease the x-ray laser output over a few millimeters of plasma length.

We report experimental results from a very simple approach where a single, flat slab target has been irradiated with two or three shorter line foci produced by placing a mask in the focusing beam. The millimeter-scale gaps in the line focus form multiple stages in the plasma column and are observed to substantially improve the beam divergence and intensity of several Ne-like ion x-ray lasers.

EXPERIMENTAL DESCRIPTION

The experiment was carried out on the Compact Multipulse Terawatt (COMET) laser system at LLNL [8]. This laser, operating at 1054 nm wavelength, utilizes chirped pulse amplification to produce the two laser beams to generate the x-ray laser. For this study on Ne-like Cr and Fe x-ray lasers, energy of 0.6 – 4.8 J in a 600 ps pulse was followed by a delay of 1.4 ns before utilizing a 1.2 ps excitation pulse with 5 J. The laser repetition rate was 1 shot every 4 minutes. The line focus length of 1.1 cm was achieved with a cylindrical lens and an on-axis paraboloid. The 600 ps beam was defocused to a width of ~150 μm (FWHM) while the 1.2 ps beam was focused to 80 μm [9]. A simple reflection echelon technique was adopted to produce a traveling wave line focus as described in previously related x-ray laser work [10]. The traveling wave optic consisted of five flat mirror segments placed before the focusing optics where each mirror segment was offset by 0.12 cm to introduce a traveling wave towards the spectrometer with a delay of 7.7 ps per step. This corresponded to a phase velocity of c along the line focus length with five steps.

The on axis x-ray laser output was observed with a 1200 line mm^{-1} variable-spaced flat-field grating spectrometer with a back-thinned 1024 × 1024 charge-coupled device (CCD). A 1 μm thick Al filter, determined to have a filter transmission of 0.032 at 28.54 nm, was used at highest x-ray laser intensities to prevent the CCD from saturating. Fiducial wires, placed in front of the spectrometer, were aligned relative to the target surface with a telescope in order to calibrate the angular deflection and beam divergence of the x-ray laser in the horizontal direction. Flat polished Cr and Fe slab targets were used in the experiment and tilted back by ~5 mrad in the horizontal direction to compensate for refraction of the x-ray laser in the plasma column. A CCD x-ray double-slit camera with 25 μm spatial resolution monitored the line focus plasma uniformity and overlap of the laser pulses. In addition to these diagnostics, several Focusing Spectrometers with Spatial Resolution in 1-Dimension (FSSR-1D) instruments using Kodak DEF film and CCD detector arrays were employed [11]. These gave $n = 3 \rightarrow 2, 4 \rightarrow 2$ Ne-like Fe and Cr resonance line emission measurements with spatial information along the length of the laser line focus.

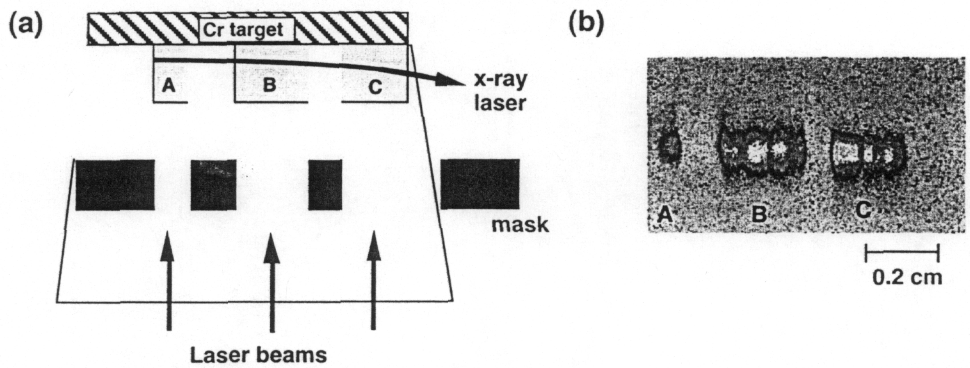

Fig. 1 (a) A mask placed in focusing beam generates three-stages A, B, and C along the Cr plasma. (b) X-ray double-slit camera image of x-ray emission showing three Cr stages clearly visible in the line focus. Magnification is 1× along the focus length and 14× across the focus width.

To compare the effect of the multi-stage target to the single stage target, it was important to maintain the same line intensity along the line focus but with the gaps. Although it would have been possible to create gaps in the line focus by simply separating the segments using the traveling wave stepped mirror, this may have changed the longitudinal intensity profile. Instead an alternative method was tried where a mask was placed in the focusing beam about 12 cm from the target. This created small gaps of approximately 1 mm length with minimal diffraction effects on the line focus. Figure 1 shows this experimental layout. The x-ray laser output could be studied with and without the gaps. A two-stage device was tried for Fe and a three-stage for the Cr x-ray laser with similar results. We report on a three-stage Cr x-ray laser using a 1 cm target irradiated with ~3 J, 600 ps and 4.8 J, 1.2 ps.

EXPERIMENTAL RESULTS

The conventional single-stage Cr targets have been reported recently [9]. Strong lasing was observed on the 28.54 nm $3p \rightarrow 3s$ line, with weaker lasing on both the 25.91 nm $3d \rightarrow 3p$ line and the short wavelength 24.03 nm $3p \rightarrow 3s$ line. An intensity versus length study was performed for single-stage target lengths of 0.2 cm to 1 cm, and small-signal gain of 31 cm^{-1} was determined for the 28.54 nm $3p \rightarrow 3s$ line for targets up to 0.4 cm. The output was found to increase at a lower exponential rate up to 1 cm. The overall gain length product of 16.7 ± 0.6 was above the predicted saturation intensity. Using this as a reference for single-stage Cr target output, the mask was placed in the beam to generate the three-stage target, as shown in Fig. 1. Similar laser pumping conditions were repeated. The x-ray laser intensity was found to be substantially higher for the combined lengths of the three stages when compared

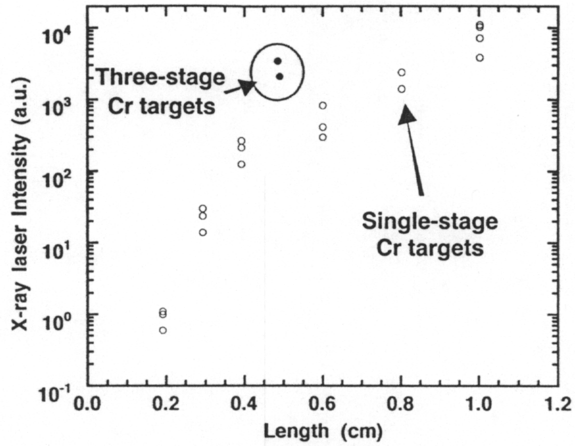

Fig. 2 X-ray laser output of the Cr 38.5 nm $3p \rightarrow 3s$ line as a function of target length for Cr single-stage (open circles) and three-stage targets (closed circles). Note that the three-stage target length is the combined length of all three stages as determined by the double-slit x-ray imaging camera.

with a single stage length. This is shown in Fig. 2 where the three-stage Cr target for 0.5 cm is higher than a 0.8 cm single-stage. For this situation, a close proximity injector-amplifier action is proposed as the explanation for the enhanced output of the multi-stage target. For nomenclature purposes, the first two stages, A and B in Fig. 1, are considered as the injector and stage C as the amplifier.

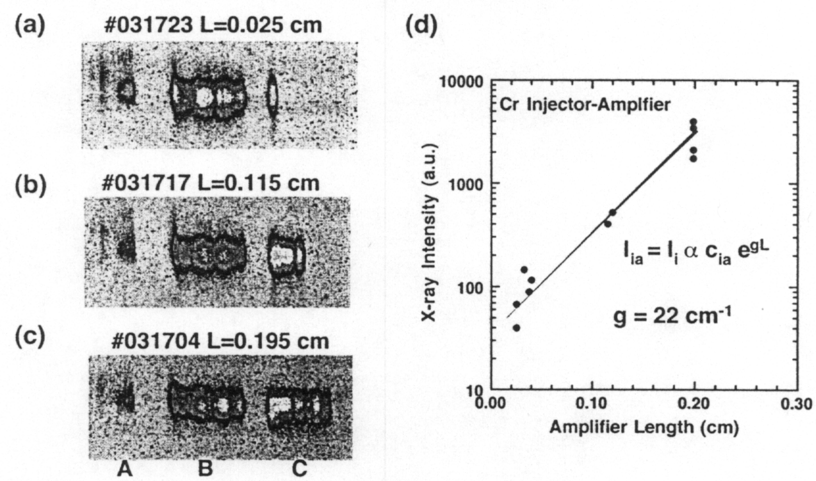

Fig. 3 (a), (b), (c) are x-ray images of the line focus where the amplifier section length, L, is varied from 0.025, 0.115 and 0.195 cm, respectively. (d) The x-ray laser output intensity of the Cr 28.5 nm line plotted as a function of amplifier length, L.

The length of the amplifier section, up to a maximum of 0.2 cm, could be varied by moving the target longitudinally in the line focus. The injector stage length (A and B) remained constant and it was possible to measure the total output from stage B, and therefore the injector intensity I_i coupled into the amplifier stage. Stage A length, a single-stage, was less than 0.1 cm and the output intensity was too low to measure. Figures 3(a) – (c) show x-ray double-slit images of the line focus plasma where the amplifier stage is being varied in length. The corresponding x-ray laser intensity of the Cr 28.5 nm line is plotted as a function of the amplifier length, Fig. 3(d). It would be expected that the injector-amplifier output, I_{ia}, can be written as $I_{ia} = I_i\ \alpha\ c_{ia}\ e^{gL} + I_a$ where I_i is the injector output, α the attenuation from cold plasma at the end of the injector and amplifier stages, c_{ia} coupling efficiency from injector to amplifier stages, g the small signal gain for amplifier length L, and I_a is the unseeded amplified spontaneous emission (ASE) from the amplifier stage. From Fig. 2 the ASE from a 0.2 cm target is ~1 count and so all of the amplifier output is due to seeding. The average small signal gain is estimated to be ~22 cm^{-1}.

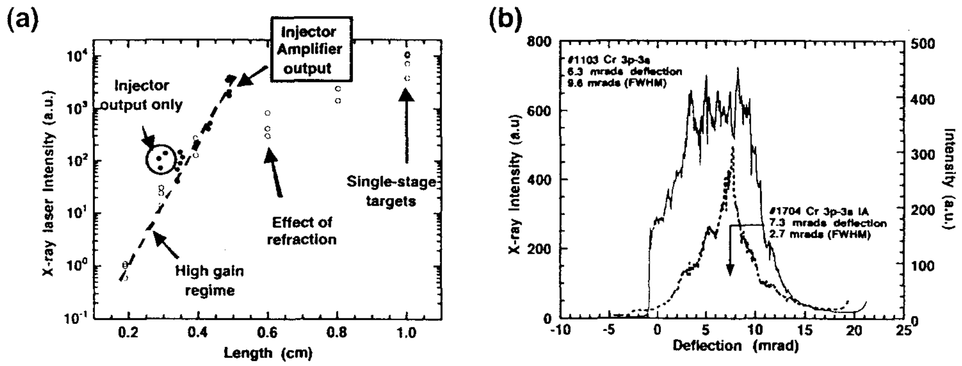

Fig. 4 (a) Cr x-ray laser intensity plotted against length for single-stage and multi-stage targets. (b) Angular pointing of a 1 cm single-stage plotted with a 0.5 cm multi-stage target.

Figure 4(a) shows the multi-stage output plotted together with the single-stage data. The overall output of the 0.5 cm multi-stage while not exceeding the 1 cm single stage output has an estimated gain length product of 15 and is close to saturation. Figure 4(b) shows the pointing angle and beam divergence of a 1 cm single-stage target and multi-stage 0.5 cm target. The single-stage deflection angle and beam divergence are similar to previous results for Ti [12, 13]. The multi-stage target although shorter has a substantially narrower beam divergence angle. Typically 2 – 3 times narrower beam divergence for the multi-stage targets was observed.

DISCUSSION

This simple injector-amplifier target architecture consisting of multiple stages demonstrates improved x-ray characteristics in beam divergence and output mainly by mitigating the effects of refraction, to be modeled in simulations. It was expected that the large scale non-uniformities in the line focus would be substantially detrimental to the x-ray laser propagation along the plasma column. This has not been the case and raises the question of beam uniformity in transient gain x-ray lasers. Secondly, at the ends of each stage regions of cold plasma will be created resulting in absorption losses by free-free inverse bremsstrahlung or photo-ionization of low Pd charge states. However, even though this setup is not ideal, the effect of creating a multiple stage target appears to maintain the x-ray laser propagating through the high gain region, Fig. 4(a), without the roll-off that affects single targets of length greater than 0.4 cm. The large spatial extent of the Ne-like gain region away from the target is expected to be important for this scheme.

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